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Pulse Period History and Cyclotron Resonance Feature of the X-Ray Pulsar 1E 2259+586

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Abstract

The results of two follow-up Ginga observations of 1E 2259+586 are presented. A secular spin-down trend was found to hold for more than 10 yr. However, the spin-down rate decreased as the X-ray flux increased for the first time in 1990. This supports a scenario that 1E 2259+586 is a binary X-ray pulsar in a nearly equilibrium state of spin-up and spin-down torque, and not an isolated white dwarf. In the X-ray spectrum, absorption features were found at 5–10 keV. The shape of the absorption features changed between the two observations and between different pulse phases. This absorption structure is likely to be due to cyclotron resonant scattering in a relatively weak magnetic field.

Key words: Cyclotron features — Pulsar — Spin-down — X-rays: Spectrum

1. Introduction

The X-ray pulsar 1E 2259+586 is located at the center of the young supernova remnant G109.1−1.0 (Gregory and Fahlman 1980), whose age is estimated to be about 10^4 yr (Gregory and Fahlman 1980; Hughes et al. 1981). The spin-down rate of 1E 2258+586 is about 6×10^{-13} s s^{-1}, which is comparable to that of the Crab pulsar. However, 1E 2259+586 has a much longer spin period (about 7 s) than any other isolated neutron star in a young supernova remnant. The mean X-ray luminosity is about 10^{35} erg s^{-1}, which is significantly larger than the rotational energy loss estimated from the observed spin period and the spin-down rate. Thus, many authors have pointed out that 1E 2259+586 is likely to be an accretion-powered binary X-ray pulsar (e.g., Koyama et al. 1987).

But 1E 2259+586 exhibits several peculiarities, as compared to an ordinary binary X-ray pulsar: (1) the pulse period shows a rather stable spin-down trend with a small rate of 6×10^{-13} s s^{-1} over the past 10 yr (Davies et al. 1990), and (2) the X-ray spectrum is softer than that of any other binary X-ray pulsar. Furthermore, there is no firm evidence for an optical counterpart (Davies and Coe 1991), and no orbital Doppler modulation has been discovered (Koyama et al. 1989, and references therein). Therefore, several authors have proposed non X-ray binary models for 1E 2259+586, such as a merged white dwarf (Paczyński 1990).

Based on the model of a binary X-ray pulsar, Koyama et al. (1987) have proposed that the soft spectrum is due to a relatively weak magnetic field (about 5×10^{11} G). The slow spin-down rate is naturally explained in this model, since the system is near an "equilibrium" state in which the acceleration torque is slightly smaller than the deceleration torque at an X-ray luminosity of about 10^{35} erg s^{-1}. Independent support regarding the weak magnetic field was given by a hint of a cyclotron resonance feature in the first Ginga observation (Koyama et al. 1989). Since the cyclotron resonance energy is a key parameter for the weakly magnetized binary pulsar model, we need a confirmation of the cyclotron resonance features.

Another important test involves the pulse period change vs. the X-ray flux, because in the model of a binary pulsar in an "equilibrium" state, $\dot{P}$ is sensitive function of the accretion rate.

In order to investigate the cyclotron resonance features as well as the pulse period changes as a function of the X-ray flux, we have carried out two follow-up observations with the Ginga satellite.

2. Observations

The observations of 1E 2259+586 were made from 1989 December 15 to 17, and 1990 August 8 to 10, using the Large Area Proportional Counters (LAC) (Turner et al. 1989) onboard the Ginga satellite. Since the LAC field of view is as large as $1° \times 2°$ (FWHM), the underlying SNR G109.1−1.0 was inevitably in the field of view.

The X-ray data in the range of 1 to 37 keV were accumulated in the 48-energy channel mode (MPC-1 or MPC-2 mode) with the medium or low bit rate. The time resolution was either 0.5 s or 16 s, depending on the data mode and the bit rate. The high-resolution data were used for a pulse timing analysis and for an analysis of pulse phase resolved spectra, while the low time resolution data were available for a pulse averaged spectrum. The total integration time for the observations during 1989 and 1990 were 3×10^4 s and 2×10^4 s, respectively.

3. Analysis and Results

3.1. *Background Subtraction*

Subtraction of the cosmic diffuse X-ray and non-X-ray background was made following the method of Awaki et al. (1991). Since 1E 2259+586 is located at the center of the supernova remnant G109.1−1.0 near the Galactic plane, we estimated the contributions of these two components. Using the temperature and the luminosity of G109.1−1.0 obtained with the Einstein observatory (Seward 1983; Fahlman et al. 1982), we found that the contribution of G 109.1−1.0 is about 1% of the total flux of 1E 2259+586 in the Ginga energy range. We therefore neglect the contribution of G109.1−1.0. The Galactic diffuse emission is a more significant contribution, even though 1E 2259+586 is located far from the Galactic Ridge. In fact, Koyama et al. (1989) reported that there is excess Galactic emission near the Perseus region. Using the Ginga satellite, S. Yamauchi (private communication) observed the Galactic diffuse emission in the region l = 115°–135°, and confirmed the excess diffuse Galactic emission. The X-ray spectrum of the diffuse emission is fitted by a thermal bremsstrahlung model of temperature about 10 keV. A strong iron line of about 1 keV equivalent width was also found (S. Yamauchi, private communication).

The X-ray flux of the blank sky near 1E 2259+586 was observed during the maneuvering operation and, was found to be of the same level as in the region l = 115°–135°. We therefore adopted the Galactic diffuse background in the l = 115°–135° region for the background of the present observations. The X-ray flux of the Galactic background is 1.5 counts s^{-1} in the 1–37 keV energy band. This is 5–10% of the total flux from 1E 2259+586. However, since the X-ray spectrum of 1E 2259+586 is rather soft, subtraction of the Galactic diffuse background is crucial for obtaining the correct X-ray spectrum at the highest energies.

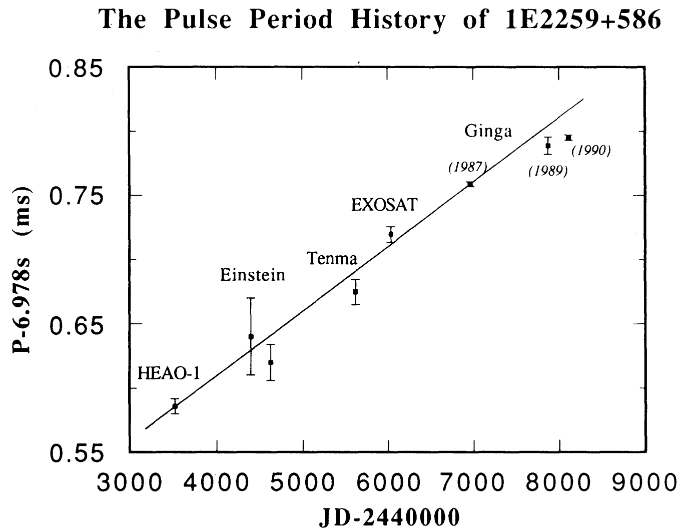


Fig. 1. Pulse period history of 1E 2259+586 from 1978 to 1990. The line is the best fit to the points before 1989.

3.2. *Pulse Period History*

With the folding technique, we have determined the heliocentric pulse period to be 6.978789±0.000007 s and 6.978795±0.000002 s for the epoch of 1989 December 15, and 1990 August 9, respectively. Since no significant value of the projected semimajor axis of binary orbit was obtained (3σ upper limit is $a_x \sin i \leq 0.08$ lt-s: Koyama et al. 1989), we neglect the orbital Doppler modulation in determining the pulse period. These pulse periods are plotted in figure 1 together with the previous observations. The pulse period monotonically increased for more than 10 yr from 1978 to 1987, with a mean spin-down rate of 6×10^{-13} s s^{-1}, as is shown by the solid line in figure 1. However, the spin-down rate provided by the latest observations is only 3×10^{-13} s s^{-1}, about half of the mean value of the previous 10 yr.

The pulse profiles in the 1.2–14 keV range after background subtraction are given in figure 2. The pulse profile of the 1989 observation (filled circles) has asymmetric double peaks with nearly equal intensities. This shape is similar to those of previous observations (e.g., Koyama et al. 1989; Hanson et al. 1988). In the 1990 observation (open circles) the main-peak became more prominent than the second-peak. The shape of the main-peak also changed dramatically; from "fast-rise slow-decay" to "slow-rise fast-decay." We note that the X-ray flux of the second observation was about two times larger than that of the first.

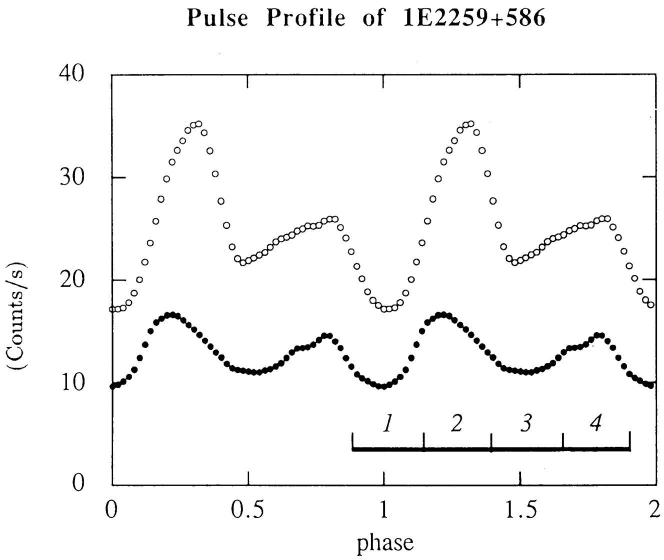
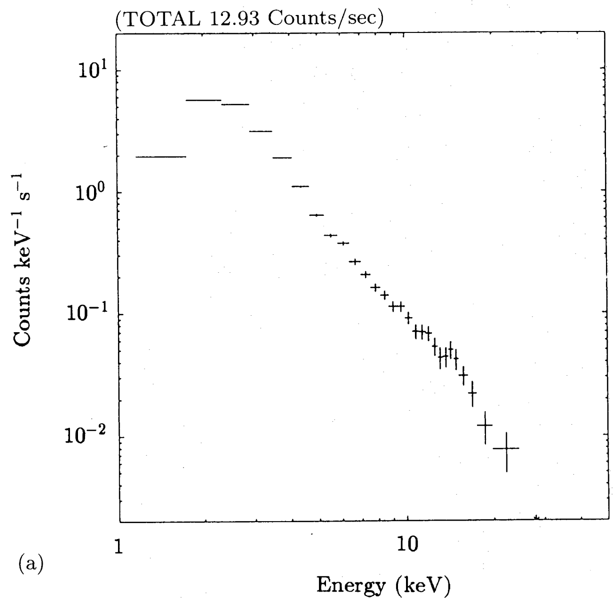
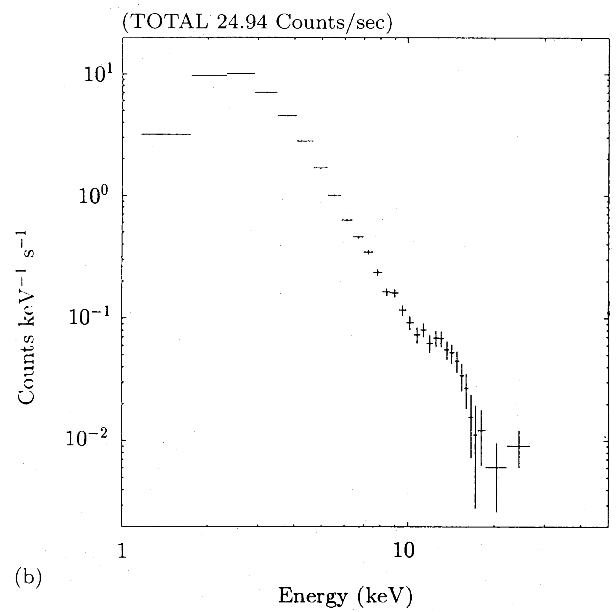


Fig. 2. Pulse profile of 1E 2259+586 in the energy range 1.2–14 keV in 1989 (filled circles) and 1990 (open circles).



(a)



(b)

Fig. 3. Pulse-phase averaged spectrum of 1E 2259+586 in 1989 (a) and 1990 (b). The Galactic diffuse background is subtracted in these spectra.

3.3. The Energy Spectrum

The pulse-phase averaged spectrum of 1E 2259+586 in 1989 and 1990 are shown in figures 3a and 3b, respectively. It is clear that these spectra cannot be described by a single component model, since there is some structure around 5–10 keV. Nevertheless, for a comparison with the previous spectra, we fitted a single power-law model to these data. The best-fit power-index, although this model was unacceptable, was 4.0 and 4.2 for the data of 1989 and 1990, respectively. Using this fit, we estimate the total flux in the 2–10 keV band to be 0.4×10^{35} erg s^{-1} (1989) and 1.0×10^{35} erg s^{-1} (1990).

Although we further tried a two-component power-law model, it was still unacceptable. In order to investigate the structure around 5–10 keV in more detail, we obtained pulse-phase resolved spectra. These spectra were normalized by the best-fit two-component power law model. The normalized spectra are shown in figures 4a and 4b, and the definition of the pulse phase slices are found in figure 2.

In the spectra of 1989, although the absorption structure at 5–6 keV is seen at all pulse phases, it is most clear in phase slice 1. In 1990, the dip structure is more complicated and is strongly pulse-phase dependent. Two dips at about 6 and 10 keV are found in phase slice 3.

4. Discussion

In the previous Ginga observations during 1987, Koyama et al. (1989) found structure around 5–10 keV. A clearer dip structure was found in the present observations, although the shape and intensity are variable. Although this structure may be related to cyclotron resonant scattering, a simple model of cyclotron absorption is rejected. This may be mostly due to an improper model function used to describe the continuum shape. Since we do not know the shape of the continuum apriori, and since our data quality, particularly the energy resolution, is still limited, it is unrealistic to fit a more complicated model for continuum emission. In what follows, we will

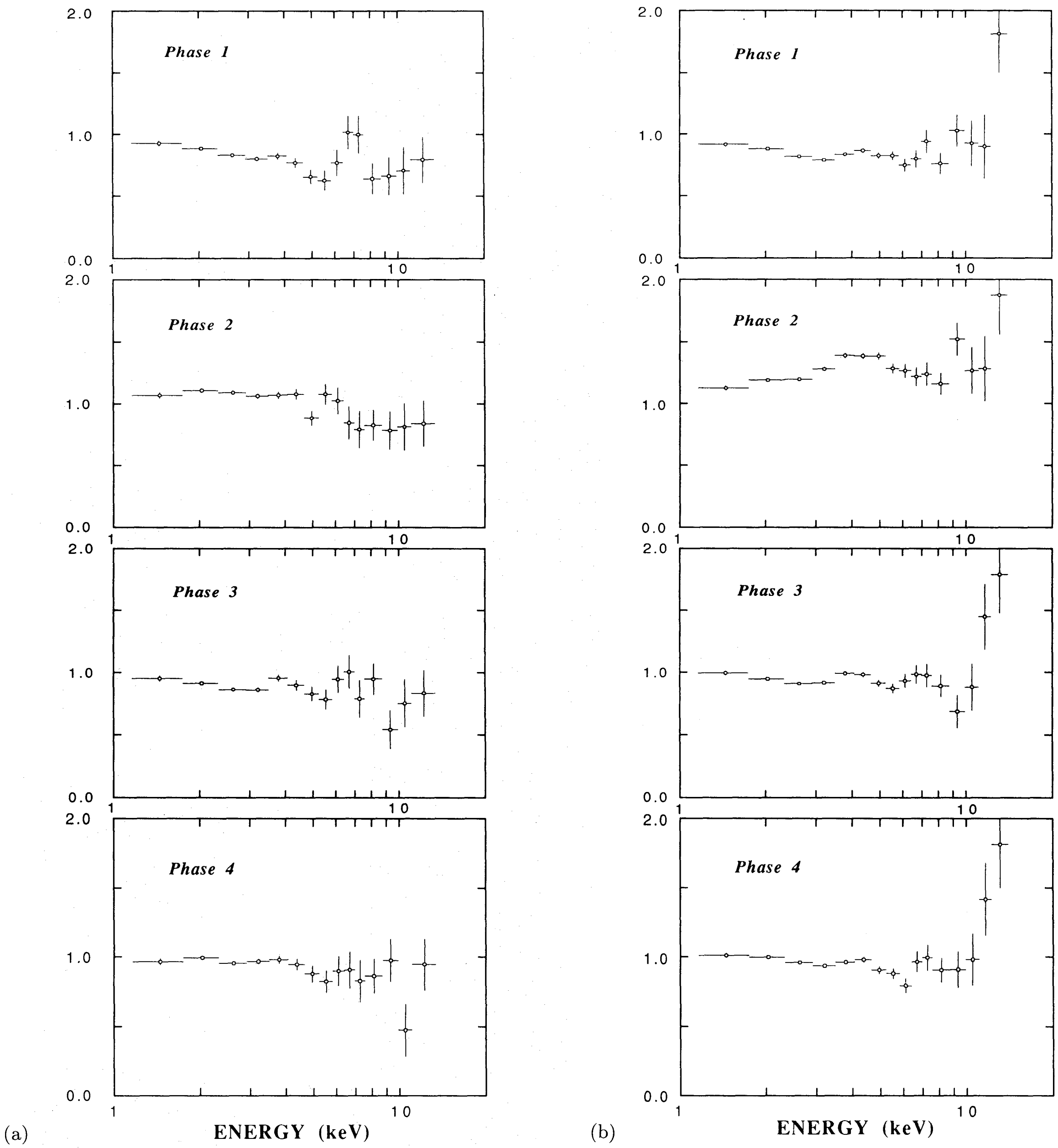


Fig. 4. Ratios of the pulse-phase resolved spectra of 1E 2259+586 to the two-component best-fit model in 1989 (a) and 1990 (b). Definition of the pulse-phase slices is found in figure 2 (see text). The two-component power law model function is described in the form $dI/dE = (A_1E^{-\Gamma_2} + A_2E^{-\Gamma_2})\exp(-\sigma N_H)$ photons keV^{-1} s^{-1}. Parameter values of the model adopted for (a) and (b) are $A_1 = 3572$, $\Gamma_1 = 5.7$, $A_2 = 4.2$, $\Gamma_2 = 1.6$ and $\log N_{\rm H} = 22.36$; $A_1 = 2766$, $\Gamma_1 = 4.7$, $A_2 = 2.5$, $\Gamma_2 = 1.6$ and $\log N_{\rm H} = 22.29$, respectively.

assume that the dips at 5 and 10 keV are cyclotron absorption of the fundamental and the second harmonic, respectively, and try to give a self-consistent picture of 1E 2259+586.

Among the pulse-phase resolved spectra observed in 1989, the spectrum of the first pulse minimum (phase slice 1) shows dips around 5 keV, and possibly at 10 keV. The dip at 10 keV became clearer in phase slice 3 during 1990. Therefore, the spectrum during 1990 would be interpreted as being the second harmonic becoming more prominent. Similar features were observed in the X-ray spectrum of X0115+634 (Nagase et al. 1991) and in the gamma-ray burst spectrum (Murakami et al. 1988). Lamb et al. (1989) pointed out that the fundamental absorption line is "spawned" by photons produced by Raman scattering of higher harmonics. The observed shape of the dip structure depends on the viewing angle relative to the magnetic field line. If the viewing angle is per-

Table 1. Measurement of the pulse period of 1E 2259+586.

Epoch:	JD−2440000	Heliocentric pulse period (s)	Satellite	Reference
1978 Jan	3522.5	6.978586±0.000006	HEAO-1	1
1980 Jul 7	4398.5	6.97864±0.00003	Einstein	2
1981 Jan 23–25	4629.0	6.978620±0.000014	Einstein	2
1983 Oct 11–14	5620.0	6.978675±0.000010	Tenma	3
1984 Dec 1–2	6036.0	6.978720±0.000006	EXOSAT	4
1987 Jun 21–23	6968.9	6.978759±0.000002	Ginga	5
1989 Dec 15	7876	6.978789±0.000007	Ginga	6
1990 Aug 9–10	8113	6.978795±0.000002	Ginga	6

1: Davies et al. 1990, 2: Fahlman and Gregory 1983, 3: Koyama et al. 1987, 4: Hanson et al. 1988, 5: Koyama et al. 1989, 6: this work.

Table 2. X-ray Luminosity and best-fit power-index of 1E 2259+586.

Observation	2–10 keV X-ray luminosity (erg s^{-1})	Photon index	Satellite
1983 Oct 11–14	0.4×10^{35}	3.7±0.3	Tenma
1987 Jun 21–23	0.5×10^{35}	~4	Ginga
1989 Dec 15–17	0.4×10^{35}	4.0	Ginga
1990 Aug 8–10	1.0×10^{35}	4.2	Ginga

pendicular to the magnetic field line, we may observe a stronger second harmonic and narrow line width. Therefore, the viewing angle of phase slice 3 during 1990 would be nearly perpendicular to the magnetic field line, while the other phases would not. A change in the accretion geometry could be due to a change in the mass-accretion rate (X-ray luminosity), and it would be responsible for the change in the pulse profile which was found between the present two observations.

From the cyclotron resonance energy we infer that the magnetic field strength is about 5×10^{11} G. This value is smaller than that found in any other binary X-ray pulsar for which cyclotron absorption features have been discovered (Makishima et al. 1990). This may present a new problem regarding the evolution of magnetic field in neutron stars, which is beyond the scope of this paper. On the positive side, this small value of the magnetic field makes the Alfvén radius nearly equal to the co-rotation radius at the observed luminosity of 10^{35} erg s^{-1}. The small spin-down rate can thus be interpreted as being a pulsar very near to its equilibrium period, as was already pointed out by Koyama et al. (1987).

The change in the spin-down rate favors a binary model for 1E 2259+586, rather than a single-star model, which provides an extremely stable spin down. In order to see the relation of spin-down rate to the X-ray flux, we re-estimated the X-ray luminosity in a common energy band for the previous Tenma and Ginga observations. Since the previous spectra have a contribution (although small) from the Galactic diffuse emission near the Perseus arm, we have subtracted this component from the previous data. The X-ray flux of Tenma and three Ginga observations in the 2–10 keV band are listed in table 2 together with the best fit power-law index. We found that the overall spectral shape does not change much, and that the X-ray flux has been constant, except for the data during 1990 in which the X-ray flux became about two-times larger than before. The spin-down rate became smaller around 1990. Thus, we suggest that the spin-down rate is anticorrelated with the X-ray flux. During the first 10 yr, the Alfvén radius would be slightly larger than the co-rotation radius. Then, in 1990, the Alfvén radius became small as the X-ray flux increased by a factor of two. The deceleration torque thus became smaller, resulting in a decrease in the spin-down rate.

5. Conclusions

As a result of two follow-up observations with Ginga, we have obtained several new pieces of evidence in support of the accreting binary pulsar model of 1E 2259+586:

1. The spin-down rate, which was marginally consistent with a constant value for the first 10 yr of observations, has decreased by a factor of 2 between 1987 and 1990. The single white dwarf model of Paczyński (1990), which requires an extremely stable $\dot{P}$, is thus now ruled out.

2. The accompanying increase in luminosity by a factor of 2 is in the direction expected under the theory of accretion torques, and is additional evidence that accretion power, rather than a cooling stellar surface, is responsible for the X-ray emission.

3. A pulse-phase dependent structure around 5–10 keV can be explained qualitatively as cyclotron resonant scattering. Although the inferred magnetic field is smaller than of other binary X-ray pulsars, it is consistent with the theory that the pulsar is nearly at its equilibrium period for an X-ray luminosity of 10^{35} erg s^{-1}.

A number of questions about 1E 2259+586 remain unresolved. The orbital parameters and the optical companion are still unknown. Even the association with the supernova remnant G109.1−1.0 is not established with certainty. But the conclusion that the pulsar is an accreting neutron star in a low-mass binary system is now much more secure.

We would like to express our thanks to all members of the Ginga team. The data analysis was performed on the FACOM M380 computer of the high energy physics laboratory of Nagoya University.

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